THE OXFORD FOLDED TANDEM

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Résumé. — L'histoire et le développement de l'injecteur Van de Graaff vertical sont résumés depuis la réception en 1965 jusqu'à son utilisation actuelle comme source intense de faisceaux de particules α de 9-10 MeV et de néon de 40-50 MeV.

La décision de convertir la machine en un Tandem *replié* est justifiée du point de vue du programme expérimental et de facteurs techniques et économiques. L'avancement de la conversion est décrit ainsi que les performances à atteindre.

Abstract. — The history and development of the vertical injector Van de Graaff is summarized from its commissioning in 1965 to its present use as a source of intense α -particle beams of 9-10 MeV and of 40-50 MeV neon beams.

The decision to convert the machine to a folded Tandem is justified in the light of the experimental programme and of the technical and economic factors involved. Some features of the folded Tandem design are discussed, the state of the conversion is reviewed and the performance goals are described.

1. Introduction. — The decision to convert the large vertical single-ended Van de Graaff at Oxford into a folded Tandem was made in 1974 after various alternative proposals for increasing the energy and quality of heavy ion beams available from the Oxford coupled accelerators had been discarded on grounds of cost or inconvenience.

The conversion was funded in 1975 on the basis that the original tank, column and analyser magnet would be retained. Allowing for inflation, the sum of £90,000 was made available by the Science Research Council for the purchase or manufacture of the new components. Preparatory work is now complete and the accelerator is ready to accept the new terminal, injectors, accelerator tubes and control system.

The Oxford injector has a large terminal (1.57 m in diameter, 2.89 m high). Additionally, the column was designed to take a differential pumping tube which, however, was never installed; there is, thus, a ready-made position in the column structure capable of accommodating the low energy tube. The two tube axes are 0.965 m apart which, in turn, means that the 180° magnet will bend a 12 MeV deuteron beam with a magnetic field of 1.425 T.

Electrostatic field calculations have shown that with 10 MV on the injector terminal both the smooth macroscopic maximum field and the peak fine structure field would be lower than those encountered in the EN, FN and MP Tandems at their upgraded

voltages. Relatively recent tests at Oxford have shown that the addition of 1.9 % SF_6 to the gas mixture, at 190 psi, allowed the terminal voltage to be raised beyond 12 MV; this test was done without tubes. It also established that the existing column, which is 5.94 m long, is satisfactory at the gradients (2 MV/m) created by 12 MV on the terminal. If one were to add 30 % SF_6 at 181 psi, then a terminal voltage of 14 MV could be obtained; this, however, would involve a lengthening of the column. The objective of the present conversion programme is the achievement of 10-12 MV terminal voltage, with no alterations to the accelerator column.

The heavy ion capability of the present coupled accelerators is restricted by the maximum terminal voltage (< 7 MV) of which the EN Tandem is capable. Operation of the folded Tandem at 10 MV, with terminal pumping, charge state selection and double stripping will result in the performance indicated in tables I and II. NS and EW sections through the centre of the accelerator show the general arrangement of the folded Tandem (Figs. 1 and 2).

2. Injector System. — Two separate negative ion injectors will be installed close to the base of the tank, each capable of transmitting a horizontal pre-accelerated beam of negative ions into a rotatable 90° inflector magnet. The injectors have independent vacuum systems, controls and power supplies. One

TABLE I

Energies and intensities for singly and doubly stripped ions from the folded Tandem at 10 MV terminal voltage

Stripper (G : gas, F : foil) Charge state, energy and intensity	G			G, F			F		
	q_1	E	i_p	q_2	E	i_p	q_1	E	i_p
		MeV	μA		MeV	μA		MeV	μA
ion — ^1H , ^2D	1	20	1.5	—	—	—	1	20	3.0
$^3,^4\text{He}$	2	30	1.0	—	—	—	2	30	1.5
$^6,^7\text{Li}$	3	40	1.0	—	—	—	3	40	1.0
^{12}C	5	60	2.0	6	67	0.4	5	60	0.5
^{16}O	5	60	2.0	7	73	0.3	6	70	0.5
^{24}Mg	6	70	0.1	9	90	0.03	7	80	0.1
^{32}S	6	70	1.0	11	100	0.15	8	90	0.4
^{79}Br	6	70	0.5	14	118	0.05	10	110	0.2

The quoted particle intensities make allowance for the source output of different ions, for the maximum negative ion beam acceptable by the accelerator tube (5 μA for light ions, decreasing to 1 μA for ^{79}Br), for charge state fraction and non-equilibrium stripper thickness, and for maximum permissible energy deposition in the stripper foils (where used).

The most probable charge states are quoted in all cases.

TABLE II

Maximum energies and intensities available from doubly stripped beams by selecting high charge states. Terminal voltage 10 MV

			First stripper				Second stripper					
	Ion	i_- μA	Type	q_1	f_1	E_2 MeV	i_{p_1} μA	Type	q_2	f_2	E_3 MeV	i_{p_2} μA
^{32}S	$q_1 \sim \bar{q}$	2	Gas	6	0.4	34	0.8	Foil	11	0.3	100	0.24
	$q_1 \sim \bar{q} + 2$	2	Gas	8	0.1	42	0.2	Foil	12	0.3	114	0.06
	$q_1 \sim \bar{q} + 2$	1	Foil	10	0.05	50	0.05	Foil	12	0.3	122	0.015
^{79}Br	$q_1 \sim \bar{q}$	2	Gas	6	0.25	34	0.5	Foil	14	0.25	118	0.12
	$q_1 \sim \bar{q} + 2$	2	Gas	8	0.06	42	0.12	Foil	15	0.25	132	0.03
	$q_1 \sim \bar{q} + 2$	0.5	Foil	12	0.06	58	0.03	Foil	17	0.25	160	0.007

i_- Negative ion beam intensity-limited by tube loading or foil life.
 q_1, q_2 Selected charge states at first and second strippers. Note : $q_2 \approx \bar{q}$.
 f_1, f_2 Charge state fraction of selected charge state after first and second stripper.
 E_2 Energy at second stripper.
 E_3 Final energy.
 i_{p_1}, i_{p_2} Beam intensity (particle μA) after first and second stripper.

injector, intended for heavy ion beams, consists of a Middleton sputter source with caesium focus similar to that which has now operated on the EN Tandem for two years with very satisfactory results. The other injector is intended primarily for negative helium beams and consists of a commercial duoplasmatron with positive beam focus coupled to a charge exchange canal of advanced design. This source may also be used for alkali metal beams.

Both these sources produce negative beams of energy 20-40 keV and emittance π (5 — 15) mm. mrad (MeV)^{1/2}. The beams are pre-accelerated before entering the analyser, which focusses the beam telescopically to an image just above its exit pole. From there the beam is refocussed by a gridded lens at the tank base and transmitted into the accelerator

tube. A conventional RF source for helium and neon beams is incorporated in the terminal.

3. Accelerator Tubes. — The accelerator tubes are made of borosilicate glass and titanium electrodes, bonded with PVA. The pitch is 19 mm, the outside diameter 330 mm. There is a gridded lens at the entrance to the negative tube, followed by a short magnetically suppressed section. The remainder of the negative tube uses spiral inclined field electrostatic suppression. Both the negative and the positive tubes are divided into a 3.65 m lower section and a 2.13 m upper section. The joint is located at the intershield support plate.

The positive tube is similar to the negative tube in that there is a short magnetically suppressed section

FIG. 1. — East-west section of folded Tandem.

FIG. 2. — North-south section of folded Tandem.

at the top, to facilitate the transmission of positive ions from the terminal source, followed by spiral inclined field electrodes. There is no gridded entrance lens. A foil stripper is located at the joint between the two sections. An upper tube section, similar in construction to that proposed for the folded Tandem, has now operated for some thousands of hours at gradients up to that which would correspond to a folded Tandem terminal voltage of 11 MV.

The accelerator tubes are pumped by 500 l/s ion pumps in the terminal and inside the tank at the base.

4. Terminal. — The general arrangement of the terminal is indicated in figure 3.

The 180° magnet was manufactured by Industrial Coils Inc. and has the following characteristics: radius = 483 mm, gap = 15 mm, maximum design field = 1.5 T, mass energy product = 25 amu.MeV. The pole tip angles are fixed and the poles themselves form part of the vacuum box. A closed water circuit will provide the necessary cooling for the coils and the magnet box. The power requirement for the magnet is 3 kW and will be provided by the belt-driven alternator in the terminal. The three-phase output (400 Hz) of this alternator will be rectified, smoothed and fed into the magnet and the quadru-

FIG. 3. — General arrangement of the terminal.

pole doublet in the terminal, which is connected in series with the magnet. The power requirements of everything else inside the terminal will be met by a permanent magnet alternator which is rated at

1.5 kW, 400 Hz. The total power dissipated in the terminal can be as high as 5 kW approximately; it is estimated that on a hot day and in view of the restricted gas circulation, the ambient temperature in the terminal can rise to 50 °C. The temperature near the coils could be near 70 °C.

Considerable thought has been devoted to the question of control of the 180° magnet to the required precision of 2 parts in 10⁴. After considering several methods of field or current detection, we have chosen to use a Hall probe. This will be thermostatically controlled to an accuracy of 0.1 %. The Hall voltage will be compared with the output of a precision DAC, set *via* the serial data link, and the difference signal will be applied to the field exciter of the 400 Hz alternator. Measurements have been made of the effect of neutron irradiation on the Hall crystal from which we are able to conclude that the critical neutron fluence ($\sim 5 \times 10^{11}$ n/cm²) (which is likely to damage other semi-conductors as well as the Hall crystal) will not be accumulated in less than a year under our expected pattern of operation. The non-linearity of the Hall probe will be measured and a suitable correction applied to the digital demand signal sent to the terminal.

Apart from the magnet, the terminal will contain a 100 position foil stripper, a gas stripper and a quadrupole doublet. Two 500 l/s ion pumps will maintain the vacuum of 10⁻⁶ torr or better in the magnet box and the top of the two accelerator tubes.

The terminal will also contain an RF ion source, mounted above the quadrupole doublet, and the necessary beam monitors and Faraday cups.

The beam envelope through the folded Tandem is shown in figure 4. Transmission of the injected negative ion beams is good, but some losses are inevitable after foil stripping of heavy ion beams due to emittance degradation beyond the acceptance of the positive accelerator tubes.

5. Serial Data Links. — In order to achieve the desired speed and accuracy of data transmission between the control console on the one hand and the terminal and ion sources on the other, multiplexed serial data links will be used in conjunction with a serial data link controller in the console. The system will be capable of interacting with existing or future on-line computer facilities (Fig. 5).

It was decided at an early stage that control of the terminal should be achieved by an infrared light link system, similar to the one that has been developed at Daresbury for the 30 MV Nuclear Structure Facility. An infrared transmitter/receiver pair is located at the base of the machine and an identical pair is located inside the terminal of the machine. Information is transmitted to and from the terminal by modulation of the infrared light beam. The electronic circuits associated with data handling in the terminal are enclosed in a doubly screened box to protect them from the voltage surges developed in the machine.

FIG. 4. — Folded Tandem 8 MV ⁷⁹BrRMS beam envelope. $\epsilon_1 = 17$ mm.mrad. MeV^{1/2}. 1. Single stripper 5 μ g/cm² $Q = 10 + \epsilon_2 = 23$. 3. Double stripper 10 μ g/cm², 10 μ g/cm² $Q = 10 + 15 + \epsilon_2 = 42$.

FIG. 5. — Folded Tandem serial data links. Sample frequency

Fibre optic normal	40 Hz	Fast channel	125 kHz
Infra-red normal	160 Hz	Fast channel	5 kHz

The Oxford folded Tandem will require 32 analogue channels in the *down* direction and eight analogue channels in the *up* direction; in addition, there are eight 10-bit digital words in the down direction and eight 10-bit digital words going up. A similar system will be used to monitor and control the two negative ion injectors, but in this case the transmitting medium will be glass fibre. Each serial link has a capacity of 64.10 bit words in each direction with cycle times of 6.4 ms (infra-red link) and 26 ms (fibre-optic link). Any one channel can be addressed for fast response in which case the sample frequencies for the selected channel become 5 kHz and 1.25 kHz respectively.

6. Summary. — The manufacturing preparations for the Oxford folded Tandem conversion are now complete. Shut down of the accelerator is imminent.

After conversion we expect to accelerate intense beams of many different heavy ions with double stripping and a terminal voltage in excess of 10 MV.

With the exception of the 180° magnet, the accelerator tubes and the data links most of the design and manufacturing work has been done inside the department. Costs have been held within the revised grant of £90,000, although inflation has consumed all contingencies and compelled some economies in design.

Acknowledgement. — The folded Tandem conversion is the joint work of many people, especially: Professor K. W. Allen, Mr. P. J. S. B-Barratt, Mr. T. R. Brock, Dr. G. Doucas, Mr. T. J. L. Greenway, Mr. A. R. Holmes, Mr. H. R. McK. Hyder, Mr. G. M. Parker and Dr. J. Takacs, and the technical and workshop staff of the Nuclear Physics Laboratory.